In presenting the dissertation as a partial fulfillment of the requirements for an advanced degree from the Georgia Institute of Technology, I agree that the Library of the Institution shall make it available for inspection and circulation in accordance with its regulations governing materials of this type. I agree that permission to copy from, or to publish from, this dissertation may be granted by the professor under whose direction it was written, if such copying or publication is solely for scholarly purposes and does not involve potential financial gain. It is understood that any copying from, or publication of, this dissertation which involves potential financial gain will not be allowed without written permission.

Stewart Warren Timmerman

A STUDY OF THE TIME EFFECTS OF

CERTAIN COMPOUND MOTION IMPEDANCES

ON MANUAL TRANSPORT TIMES

12 R

A THESIS

Presented to

the Faculty of the Graduate Division

Georgia Institute of Technology

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Industrial Engineering

By

Stewart Warren Timmerman

September 1955

A STUDY OF THE TIME EFFECTS OF

CERTAIN COMPOUND MOTION IMPEDANCES

ON MANUAL TRANSPORT TIMES

Approved:

Date Approved by Chairman: 6/17/55

ACKNOWLEDGEMENTS

The writer would like to take this opportunity to thank Doctor W. Dale Jones for his guidance and willing assistance in performing this research. He would also like to thank Doctors Edward H. Loveland and Joseph J. Moder, Jr. for their help and advice. Particular appreciation is due Elizabeth Timmerman for her encouragement, assistance, and patience.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

SUMMARY

Synthetic time study is a technique for determining the normal time for a given motion pattern by the application of predetermined time values to this motion pattern. It can be most accurately applied in behalf of unimpeded manual movements. The time synthesis of movements entailing but one impedance, such as the care necessary to steer the hand when moving an object to a target, is not generally problematical. The time synthesis procedure for movements entailing two or more impedances, however, is quite controversial. The controversy is over the question of whether the time effects of two or more impedances occurring together is equal to the sum of the individual impedance times when the impedances occur separately. The object of this research was to determine, for typical conditions, the answer to this question.

The impedances investigated were the result of; a movement of the left-hand simultaneously and identically with that of the right-hand, a movement necessitating care in approaching a small target, and a movement involving the necessity to steer under an obstruction. These impedances were investigated by involving them both singularly and in combination with a fifteen inch transport-movement.

It was evident that ordinary methods of timing would be inadequate due to the short time intervals involved. This was complicated by the fact that the inherent error in most conventional timing methods approximated the magnitude of the interval under investigation, namely the length

of time added to a basic (unimpeded) movement by an impedance. To meet this need an especially developed timing device was utilized. This timing device, which was developed by Doctor W. Dale Jones, was capable of automatically recording movement times to the nearest interpolated 0.0001 minutes.

Five subjects were utilized for the present experiment. They were selected from a group of twenty male college students by the use of a pre-test. The criterion used for the selection of the experimental subjects was consistency of movement speed. Only those students exhibiting highly consistent movement speed were selected as experimental subjects. The fifteen inch movement containing the impedance was performed between two fifteen inch basic (unimpeded) movements in one rhythmic motion pattern. The times necessary to complete the two basic movements were compared in order to determine the consistency of the students.

The selected subjects' recorded performances were similar to the pre-test performances. They consisted of a fifteen inch impeded movement performed between two basic movements. The impeded portions of these performances were assumed to have been performed at the average pace of the basic movements preceding and following the impeded movement. The average of the two basic times for each performance provided a means of applying a speed-rating factor to the accompanying impeded movement time for the purpose of normalizing it, thus correcting for differences in movement speed among the experimental subjects. The validity of this normalized time had no effect on the results. The performances were accomplished at a brisk pace, typical of that used by workers motivated by wage incentives, in order to obtain realistic performance times and to minimize variation of same.

The average of the normalized slow-down times for the single and compound impedances (two or three impedances encountered in the same movement) were calculated for each subject. The normalized slow-downs caused by the individual impedances were added in order to compare these synthesized slow-down times with the normalized slow-down time actually produced by the compound impedances. The results of this research indicate that, for the typical impedances tested, the sum of the individual (the synthesized) normal slow-down times for impedances comprising a compound impedance is significantly greater than the normal slow-down time produced by the compound impedance.

CHAPTER I

INTRODUCTION

Background.--Just as industry has been constantly striving to improve its methods of production through the use of industrial engineering practices, so has the industrial engineer been attempting to increase the accuracy of his time study methods. Toward this end some practitioners have advocated the use of synthetic motion and time studies, claiming that they produce more accurate and consistent results. Unlike the usual method, where the stop watch is used to measure combinations of the fundamental movements making up tasks, the synthetic method makes use of predetermined movement time values. These time values have been largely determined by experimentation and are usually presented in tabular form. After a time study technician has determined what fundamental movements make up a particular task, all that is necessary is to refer to the proper movement time data table to determine the estimated normal time for the performance of these movements. Simple addition of the estimated movement times will produce the estimated normal time for the completion of the task. Therefore, the accuracy of the synthetic time study depends upon the reliability of the predetermined time values while its consistency depends upon the ability of the time study man.

Synthetic Motion and Time Study.--Synthetic motion and time study, hereafter referred to as "synthesis", is a form of standard data. While standard data is concerned with elemental times for a particular task, synthesis deals with fundamental movement times which may be applied to any task. By the application of the synthesis it is possible to estimate the normal time for a task before the task is actually performed. As such, synthesis is a very effective motion study tool; it permits the engineer to select the motion pattern which most efficiently completes the task. The application of the predetermined time values to the motion analysis produces the estimated normal time for the task.

Another important advantage of synthesis is that it may be used in behalf of extremely short cycle operations where the inherent error in reading the stop watch would appreciably affect the results. Synthesis is also advantageous in training operators, as it reduces the job to the fundamentals which may be taught and learned with ease. It also teaches workers, engineers, and supervisors to become motion conscious.

Several well known synthesis systems are in use today. However, synthesis has not enjoyed widespread acceptance. Perhaps the most important objection given by its critics has been the secrecy surrounding the determination of the data. Since the accuracy of the normal time as found by synthesis is a direct result of the accuracy of the predetermined time values, it is essential that these data be valid. Without the knowledge of their derivation there is no way to determine whether the data have a valid scientific basis. Investigation has revealed probable significant differences in the normal times established by these systems, suggesting a lack of validity in at least all but one set of these data.

The difficulty in applying synthesis had tended to retard its development as much as any other single factor. A high degree of skill in motion analysis and synthesis usage is necessary in order that the predetermined data will be applicable to the motion pattern breakdown. This skill can be acquired only after much training and practice.

Other objections of synthesis are: its limitation to unskilled bench type operations; the failure of some systems to recognize the time effects of the preceding and the following movements in reference to a given movement; the disregard of the effect of the direction of a motion on the time necessary to complete the motion; and the assumption that the fundamental movement times are additive.

In spite of its many shortcomings, synthesis has provided the necessary extension of standard time data to short cycle operations. It has proven a very useful tool when properly applied within its limits. Universal acceptance of synthesis is awaiting further research which will permit the extension of these limits.

The Problem.--Movement times selected from synthesis tables are added in order to determine the normal time for a given task. However, the movements for which the times are derived are not always fundamental; they are sometimes complicated by the addition of certain impedances. An unimpeded movement, hereafter referred to as a basic movement, is characterized as a "free movement", one which does not entail any restriction. An example of a free movement is moving the empty hand in any easily accessible direction but to no specific location. The normal time necessary to complete a free movement of the hand for a given distance would not be the same as the normal time necessary to complete an impeded movement for the same distance. As a result, synthesis tables list time values for the various impeded movements as well as for the basic movements. An impedance is a hindrance which slows the performance of a movement. The most familiar impedance is resistance that must be overcome ---- that is, weight to be lifted. The handling or sensory requirement necessary when moving a fragile object is another familiar impedance. A sensory requirement is exemplified by the care or mental control necessary to avoid a change of finger pressure when handling a fragile object. It is the sensation transmitted through the nerves that reflects the amount of pressure being applied. Other impedances are bimanualness and eye-hand coordination.

The time synthesis procedure of movements entailing but one impedance, such as the care necessary to steer the hand when moving an object to a small target, is not generally problematical. The time synthesis procedure for movements entailing two or more impedances, hereafter referred to as a compound impedance, however, is quite controversial. The controversy is over the question of whether the time effects of the two or more impedances occurring together is equal to the sum of the individual time effects of the impedances occurring separately.

A meaningful description of the objective of this thesis can be presented through the use of a simple example. Assume that an engineer, with a table of predetermined movement times in hand, is desirous of synthesizing the normal performance time of a manual bench-work operation. One part of the operation involves reaching fifteen inches to grasp a hammer. No motion impedance is encountered. The time synthesis of this reach would involve the selection from the predetermined movement time table a value for a free, basic fifteen inch movement.

Now, assume another part of the operation involves reaching fifteen inches to grasp a cotter pin. A motion impedance is encountered because of the smallness of the cotter pin. Time synthesis of this motion would, therefore, involve the selection of a value from the time-data table for the slow-down caused by the single impedance under consideration. This value would then be added to the value listed for the fifteen inch basic movement in order to synthesize this movement.

Going a step further, assume that the operation involves reaching fifteen inches to grasp another cotter pin which has been inserted at a previous work station into the part being assembled. This pin was only pushed in place temporarily since the operator in question must remove it to complete his part of the assembly operation. The pin is not in an easily accessible location and the operator must steer his movement to reach the pin. This reach motion, therefore, involves two impedances: one for the smallness of the cotter pin and one for the necessity of reaching to a restricted area.

The exact procedure which the engineer in question will use in order to synthesize this motion will depend upon what synthesis system he is utilizing. The various systems and their different methods of handling compound impedances will be discussed later. For the purpose of this example assume that the engineer's time-data table lists time values for the basic movements and time values for the slow-downs caused by the individual impedances. In order to synthesize this movement the engineer would determine how many impedances were involved in the movement and what they were. He would then refer to the slow-down times listed in the time-data table for these impedances and add them to the basic time listed for this movement. In effect, the engineer adds the slow-down due to the impedances occurring separately in a fifteen inch movement to arrive at the total slow-down caused when these same two impedances are encountered together in the same fifteen inch movement. Adding the time for a fifteen inch basic movement to this total time then gave the time for the fifteen inch compound-impeded movement.

The engineer, mentioned above, assumed that the time effects of the two impedances occurring together were equal to the sum of the individual time impedances occurring separately. This is the generally accepted practice. It assumes that there is no significant interaction between the two or more impedances. This assumption may or may not be valid. Since many movements performed in industrial work entail two or more significant impedances, an investigation of their time effect appears warranted.

CHAPTER II

LITERATURE SURVEY

History of Synthesis.--Frederick W. Taylor, the founder of stop watch time study, originated the idea of developing predetermined, manual-work, time values around 1900. He stated:

> No system of time study can be looked upon as a success unless it enables the time observer, after a reasonable amount of study, to predict with accuracy how long it should take a good man to do almost any job in a particular trade, or branch of a trade, to which the time observer has been devoting himself.
>
> It is true . . . . that all of the work done in a given trade can be divided into a comparatively small number of elements or units, and with proper implements it is comparatively easy for a skilled observer to determine the time required by a good man to do any one of these elementary units (1).

Taylor envisioned a collection of time study standards which would encompass virtually all possible work situations, thus eliminating the need for stop watch studies except in unusual cases (2). However, a library of these times could hardly be considered basic motion time standards since the time values would be elemental times. Basic motion times had to await the development of two things: first, the breakdown of motions into basic movements; and second, a timing device which would allow measurement in such small increments.

Frank B. Gilbreth and Lillian M. Gilbreth assisted materially in the advance of predetermined motion and time study when they developed the first breakdown of human work into seventeen separate categories called therbligs. They also developed a film analysis technique which would allow accurate timing of extremely small divisions of work (3). The same technique can be used today for even more refined timing through the use of high speed photography.

Between 1900 and 1930 very little was done with synthesis; a few standard data systems were developed. These systems, involving treatment of large work divisions, i.e., multi-movements, were necessarily limited in their application. The first effort to formulate predetermined time values for single basic motions was made shortly before 1930, when Asa B. Segur evolved the Segur "Law". This law states, "Within practical limits the times required to perform true fundamental motions are constant (4)." This law might be called the basis for all synthesis systems. However, since Segur has not defined the "practical limits", his law is not too meaningful as such. As a result of his investigations concerning basic motions Segur developed a synthesis system called Motion-Time-Analysis. The timing device used in developing his data for this system was a kymograph (5). A kymograph is a machine which records time values by means of lines drawn on a synchronously driven paper tape. Extremely short intervals may be timed accurately by its use (6). Motion-Time-Analysis is a very refined system in that it treats fundamental body movements and sensory reactions. A refined synthesis system provides means for analyzing and evaluating individual movements in the smallest detail. Accordingly, mastery of its usage requires extensive, specialized training. Since its inception, the derivation of the Segur data has been kept a closely guarded "business" secret and the system has been administered only by the A. B. Segur Company. Because of this, no information concerned with the validity of the data is available to the public.

The first synthesis system to be published in detail for the public was developed for the General Electric Company around 1935 by Harold Engstrom and his associates. Suitable motion classifications were developed by extensive motion picture studies (7). The motion classifications chosen were not individual motions but small combinations of motions. As a result, this system is limited to certain types of appliance assembly operations for which it was specifically designed.

The next significant synthesis system appeared in 1938 with the publication of Applied Time and Motion Study by Walter G. Holmes. Holmes calls his system Body Member Movement Times. Like Segur's Motion-Time-Analysis, it entails a very refined breakdown of individual body movements and sensory reactions (8). Accordingly, it is intended for use on any type of manual operation. Although the derivation of Holmes' data has been published in detail, very limited application of his system has been made. This is probably due to the complexity and refinement of the system and its lack of promotion. It is doubtful whether anyone except Mr. Holmes has completely understood its application. Contemporaneously, another refined, yet more easily learned, synthesis system was developed. It was called the Work-Factor system, and was specifically designed to establish incentive rates for mass production and short cycle operations. "The original research for the Work-Factor system was of such a nature that measurements were made in times of 0.0001 minutes (9)." Because it was easier to apply than its predecessors, the Work-Factor system proved successful.

Through the application of the Work-Factor system to work cycles entailing numerous movements of different time determinant character, the authors of the system reasoned that sufficient precision in estimating cycle times could be achieved by a less refined procedure. Thus, the Simplified Work-Factor system was developed for use with non-repetitive or long cycle operations. The Simplified Work-Factor system differs from the refined Work-Factor system in that it treats combinations of movements rather than individual movements. Thus, through its use time standards for non-repetitive or long cycle operations can be established more rapidly and economically than via the refined Work-Factor system. However its use called for a thorough knowledge of the refined Work-Factor system. As a result, another system called Abbreviated Work-Factor was developed. Its use and breakdown is similar to the Simplified Work-Factor system but it fills the need for a more easily learned system (10).

The Methods-Time Measurement system authored by Maynard, Stegemerten, and Schwab was a synthesis system developed toward the end of World War II. It differs from the refined Work-Factor system in that combinations of movements rather than individual movements are treated separately. Methods-Time Measurement, like Abbreviated Work-Factor, tabulates a limited number of possible combinations of time values for certain combinations of movements. The authors have simplified their data to the point where it can all be placed on one small card. They have made available to the public the methods used in collecting and analyzing their data, as well as detailed descriptions of their application (11).

The most recent synthesis system, which is similar to Methods-Time Measurement, is that developed by J. D. Woods and Gordon, Ltd. This system is called Basic Motion Time Study. Again, combinations of movements are the basis for the predetermined time values. Throughout the development of the system the authors have attempted to build into it ease of understanding. They have tried to produce a system that is easier to teach, learn, and apply. The time data of this system are also listed on one small card.

All of the latest synthesis systems are generally similar in structure. They use combinations of motions as a basis for their predetermined time values as a means of simplifying application. The differences among these systems appear in the motion breakdown. The trend toward simplification of synthesis, through the treatment of larger movement divisions, has decreased the time estimation precision attainable via the treatment of individual movements. However, this simplification has markedly extended the usage of synthesis in motion study training and in the application of motion study.

Advantages of Synthesis.--Perhaps the most important advantage of synthesis is that it forces the user to become motion conscious. Since the normal time for a given task is estimated by the addition of predetermined time values applied to a motion pattern breakdown, the act of breaking down the task into its motion pattern stimulates motion consciousness. The close relationship between motion study and synthesis is suggested by the authors of Motion-Time Measurement as follows, "The method determines the time, and the time establishes which method is best. It is felt that the Methods-Time Measurement Procedure . . . . which considers methods and times simultaneously, solves the difficulty in cases where it is applicable (12)." Herbert Lynch, in writing for the Journal of Industrial Engineering, felt so strongly about synthesis inducing motion consciousness that he indicated that this advantage alone would justify its use (13).

By using synthesis as a motion study tool, the determination of just how a task is to be accomplished may be developed from the individual motions. Since time standards may be determined before production starts, more realistic cost estimates may be obtained. Predetermined time standards, released when the job starts, will eliminate "holding back" on the part of the operator until the standards are set.

Time standards are likely to be more consistent when established by synthesis than when established with the stop watch. This is mainly due to the fact that the difficult and controversial discernment of rating a time study is replaced by the selection of a proper motion pattern. Not only is this a far simpler decision but it offers fewer choices. Therefore, the results are likely to be more consistent. Since synthesized time standard is made up of a great deal of small time estimates which are added together, a greater chance is allowed for the plus and minus errors in the estimated normal times of the parts to cancel out than is the case in stop watch time study. This tends to give more consistent normal cycle time estimates and as a result, more consistent job time standards (14).

Synthesis systems generally deal with more refined job breakdowns and descriptions than do stop watch studies. These job breakdowns have been advantageous in teaching new operators their jobs. P. J. Brady, when discussing the Work-Factor system claimed that in some cases, after the application of synthesis, job training periods were cut in half (15).

Another important advantage of synthesis is that it tends to minimize rate grievances. It is generally considered that the stop watch, the hated symbol of "efficiency", has accounted for considerable labor trouble. Its relegation to a minor role would, therefore, be an advantage. The fact that synthesis accomplishes this objective and at the same time produces more consistent time standards explains why grievances over time standards are generally reduced via synthesis.

The most recent synthesis systems, when properly applied, have proved very successful. They have provided the necessary impetus which may someday fulfill a vision which Robert MacLatchie expressed this way," . . . . the day is not far off when industry will discard the stopwatch, will abolish leveling and will establish time study rates directly from fundamental motion-time standards" (16).

Disadvantages of Synthesis.—The most widely discussed disadvantage of synthesis has been the secrecy surrounding the determination of the basic motion times. The sentiment regarding this is best described by Gomberg who wrote:

> What is the reaction of a union engineer to be then when he is confronted by a nationally known consultant who assures him that it is possible to measure the time that it should take a skilled person to perform elementary motions to an implied accuracy of one one-hundred thousandth of a minute? Yet I have a manual in my possession which gives figures to such an accuracy and expects us to respect synthetic standards built on these figures. If at least the methods by which these figures were obtained were published, we could weigh them intelligently, but this professional knowledge is treated as a business secret (17).

Gomberg's reference was to Segur, whose confidential manual had come into his possession. Secrecy is not in the best interest of the industrial engineering profession. It has created suspicion and has prevented evaluation and constructive criticism. As a result, the authors of the more recent systems have published their data and their supporting evidence for the public.

Partly as a result of the secrecy mentioned above, several investigations were conducted to determine if significant differences existed between the time synthesis produced by the various systems. One such investigation, conducted by H. O. Davidson, concluded that the motion times arrived at by the Work-Factor, Holmes', and Methods-Time Measurement systems differed significantly (18).

Evidence intended to support the accuracy of the Methods-Time Measurement system was published by its authors (19). It consisted of a comparison between stop watch standards and Methods-Time Measurement standards and, therefore, did not support the validity of the system in any way. It compared two systems, neither of which were proved valid. The validity of some systems have been questioned on the basis of the fact that rating was used to level the synthesis data. It, therefore, follows that one of the most questionable parts of stop watch time study could have been incorporated into synthesis.

None of the present synthesis systems is capable of establishing time standards for work involving a high degree of skill. Accordingly, they lack the ability to cope with all jobs and must be used within the limits set by their development. Jobs which subject the whole or parts of the body to undue fatigue cannot be synthesized accurately since the problem of fatigue allowance remains unsolved. Also unsolved is the allowance necessary for jobs involving non-repetitive work where hesitations and false motions prevail.

Another disadvantage of synthesis results from the complexity of its application. The refined synthesis systems treat work in its smallest divisions, i.e., movements and sensory reactions. As a result, the training of analysts not only requires a longer time than the less refined or "abbreviated" systems but also requires highly skilled instructors. The simplified systems, with their less refined data, are not subject to this disadvantage. They have sacrificed accuracy and are more limited in their application. Herbert Lynch, when considering the limitations of synthesis, stated that both the refined and abbreviated systems require "judgment of a high order to decide exactly what motions could and should be employed by the 'average' qualified operators who perform the work cycle; whether certain motions can be performed simultaneously with the right and left-hand, whether grasps and positionings can take place without the eyes being focused on point of contact, and other difficult considerations (20)."

Mundel stated another objection to synthesis, as follows: "Experiments have shown that therblig times are influenced in a complex fashion by the preceding and following therbligs, as well as by other factors, and consequently can, in most cases, hardly be given as independent values (21)." One of the experiments on which Mundel bases this conclusion is Studies of Hand Motions and Rhythm in Factory Work. This experiment involved a study of the times necessary to carry, position, and place small cylinders in a hole with a beveled mouth opening. All portions of the experiment were kept constant except the amount of bevel. As was anticipated, positioning time was found to vary indirectly with the amount of bevel. However, it was found that although the transport time varied, the path and distance of the transports remained constant (22). Basic Motion Time Study is the first synthesis system to consider this relationship: movement times are tabulated for five different types of terminating motions. The authors also found that the care necessary for grasping and placing objects affects the time for the movement in a like manner, and that precision allowances increase as the distance moved increases. Provision has been made in the Basic Motion Time Study time-data table to allow for these effects.

Findings Relevant to the Problem.--The controversial part of synthesis under investigation is the handling of compound-motion impedances. For example, the Work-Factor system treats each impedance as a factor. The factors listed are: weight, or resistance; directional control, or steer; care, or precaution; change of direction; and definite stop. The dexterity necessary to perform a motion is converted into these factors which are "interchangeable in terms of their effects on the time required to perform the motion (23)." One impedance would be assigned one factor; two impedances involved in a single motion would be assigned two factors; three impedances would be assigned three factors; and four impedances would be assigned four factors. The Work-Factor table lists the times needed for basic motions of various distances and the times needed for impeded motions involving one, two, three, and four impedances (factors). The increase in time due to the addition of another factor varies somewhat, but in most cases is almost a constant. This is particularly true of movement distances of from fifteen to twenty-four inches for the first three factors. The amount added by a fourth factor is somewhat less in almost every case. The amounts added by the first through third factors for a fifteen inch movement are 0.0020, 0.0021, and 0.0021 minutes respectively; the addition of a fourth factor produces a time increase of 0.0016 minutes (24).

In summary, the Work-Factor method of handling a compound impedance can be best explained with the following example. A movement of the hand involving a fifteen inch transport of a radio tube grid to as assembly jig might involve two factors; one factor for the care or precaution necessitated by the fragility of the grid and one factor for the directional control needed to align the grid legs with the holes in the mica into which it is to be mounted. The estimated normal time for this transport would be found by referring to the arm movement data table and selecting the time listed for a fifteen inch, two factor movement.

The Abbreviated Work-Factor system allows for impedances by the addition of "Abbreviated Units." These units are used for the computation of the normal time for a task and are 0.005 minutes in duration. The simultaneous motion allowance is one unit, regardless of where it is utilized. Additional units are also added to compensate for the effect of weight. For example, one additional unit is added to a transport movement involving carrying or pushing a weight in excess of two pounds. Other impedances are allowed for by the determination of the proper transport classification; a "class #1" transport takes one unit to complete while a "class #2" transport takes two. However, one impedance or several may still produce a "class #2" transport; since it is the most complicated transport the data table lists.

Another method of handling impedances, which differs from that chosen by the authors of the Work-Factor system, is the method used in the Methods-

Time Measurement system. The time values are tabulated with various impedances listed separately with the exception of weight which is allowed for by a multiplying factor (25). H. O. Davidson pointed out that for a particular elemental time to have specific meaning it must be assigned to a "unique" element, one that "cannot be reduced to sub-classes having significantly different time values among themselves (26)." The Methods-Time Measurement system does not satisfy this criterion. The phrase "cannot be reduced to sub-classes having significantly different time values among themselves" refers to the fact that a time for a particular element would be the only time value that the element could have. If a particular element could be further subdivided into smaller individual elements with significantly different time values then the element is not "unique". Davidson gave examples of Methods-Time Measurement elements which could be further subdivided. He also stated that the "Principle of the Limiting Motion", explained below, also denies the uniqueness of the elements. The authors of this system used this "principle" in their data and offered the following analogy as an example of a limiting motion:

> a simple example, ... the reading of a letter while riding to work, is considered. While being transported to a destination, the reading of the letter is accomplished. On the assumption that the time for traveling is fifteen minutes and the reading time is five minutes, both tasks are accomplished within the fifteen minutes of traveling time. In this instance, the traveling time would be the limiting factor. If the letter were read after arriving at the destination, the time required for the two operations would be fifteen minutes of traveling time plus five minutes of reading time, or twenty minutes in all. By combining the reading of the letter with the traveling, the time for performing the two operations is reduced by twenty-five per cent. The same reasoning applied to motions. If two or more motions are combined or overlapped, all can be performed in the time required to perform the one demanding the greatest amount of time, or the limiting motion (27).

This method of handling compound impedances indicates a disregard for their effect. The movement times cannot be applied to some combinations of compound impedances.

The Basic Motion Time study system lists time values for five types of "reach or move" motions of various distances. The selection of the applicable time depends on the act which terminates the motion. A "precision" allowance is added to the move time to allow for grasp or release requiring exact location of the finger tips. A similar addition is used for simultaneous motions. The selection of the time value for simultaneous motions is determined by the distance moved and the required distance between the finger tips in order to grasp an object. Again, no provision is made for possible slow-down due to some combinations of compound impedances (28).

Mundel, in his book Motion and Time Study, Principles and Practice, advocates the use of "objective rating" when making time studies. When objective rating is used the observed pace is compared to an "objective pace standard" which is a constant. The rating is made without regard to difficulty of the job under observation. Rating is later estimated by a process which Mundel calls "secondary adjustment". Each element is rated separately. Similarly, each element has its secondary adjustment. The secondary adjustments consider:

1. Total amount of body involved in the element;
2. Foot pedals used during the element;
3. Bimanualness of the element;
4. Eye-hand co-ordination required to perform the element;

5. Handling or sensory requirement of the element;

6. Resistance that must be overcome on the element -- that is, thrust on levers, or weight lifted (29).

These adjustments are not unlike the impedances under investigation. They are listed in tabular form in varying degrees of difficulty. In discussing objective rating Mundel states:

> The total secondary adjustment for an element will be the simple sum of all the appropriate values from the scales (tables) for all of the factors.
>
> As far as is known at present these factors are additive. No complex interaction has yet been found at the element level (30).

The factors mentioned represent the increase in time due to the addition of an impedance to a basic movement. Mundel states that the time effect attributable to combinations of more than one of these factors, or impedances, in a single movement can be determined by adding the individual impedance times.

Conclusion.--The present systems, when not overextended, have proved successful in spite of their many shortcomings. This probably results from the experience of the analysts who apply these systems. They recognize the particular systems' deficiencies and, therefore, minimize their effect or compensate for them. Since the present systems are generally difficult to apply, the fact that they have a number of shortcomings increases the need for thoroughly trained and experienced analysts. In this light the need for a more accurate and more easily applied system becomes even more apparent. Such a system must be constructed on a firm foundation. This foundation will depend upon understanding the actions and interactions of the basic motions. A solid foundation has yet to be built. It is toward this end that the present investigation of the effects of compound, motion impedances is directed.

CHAPTER III

INSTRUMENTATION AND EQUIPMENT

Introduction.--The time effects of various impedances, when encountered singularly and in combination, had to be determined by experimentation. In order to do this, a suitable movement as well as a suitable method of timing had to be found. The movement chosen consisted of moving a peg a distance of fifteen inches and returning to the original starting point. It was evident that ordinary methods of timing would be inadequate due to the short time interval involved. This was complicated by the fact that the inherent error in most timing methods was of approximately the same magnitude as the interval under investigation, namely the length of time added to a basic movement by an impedance.

It would be possible to time the tested movements via micro-motion time study. However, extremely high-speed photography would be necessary to permit timing with the desired accuracy. This approach was discarded for two reasons; the high film cost and the great amount of analysis time inherent in this procedure. A specially designed automatic precision timing procedure was developed for the experiments. In order to accomplish this procedure the experimental test-board, to be described, was devised.

Experimental Test-Board.--The experimental test-board was designed to be a part of the work-place. A photograph of the test-board may be seen in the Appendix, Figure 1. The test-board consisted of a plywood base mounted at the corners on rubber "feet". The rubber feet prevented any movement of the test-board during its use. The base was painted with non-gloss light green paint since this color is generally considered to be least irritating to the eyes.

The fifteen inch forward and return movement, mentioned previously, was to take place between an electric switch button mounted in the test-board base and a target painted on the test-board base. Since one of the impedances was the use of the left-hand simultaneously and identically with the right, a second electric switch button was provided. The two electric switch buttons were seven-eighths of an inch in diameter and were mounted one and one half inches from the end of the test-board nearest to the subject. The tops of these buttons were rounded and they extended five-eighths of an inch above the base. Two similar buttons were placed fifteen inches further away from the subject. However, these buttons were flat on top and were mounted flush with the base. The distance laterally between like buttons was four inches. Four inches was selected so that, during simultaneous movements, the hands of the experimental subjects could be kept as close together as possible without interfering with one another. A movement of this type was suggested by the results of research by R. M. Barnes and M. E. Mundel involving simultaneous, symmetrical, hand motions (31). This was necessary to prevent undue eye fixation and to permit a true simultaneous movement rather than a movement where one hand tends to lead the other.

The right-hand electric switch button activated a very small micro-switch. This button, which required very little pressure in activating the switch, was connected to a timing device so that when touched a mark was relay-posted on a paper tape within the timing device. This button will, hereafter, be referred to as the "posting" button. The timing device will be discussed later. The left-hand electric switch button in front of the subject was a dummy. Its sole purpose was to serve as a target for the left-hand during simultaneous performances. This button will, hereafter, be referred to as the "dummy". The two buttons in the rear of the test-board served as small targets in timing the impedance due to a small target. These buttons will, hereafter, be referred to as "target" buttons. The target buttons each controlled a small neon lamp so that when they had not been contacted by the subject the fact would be made known to the experimenter by the absence of the glow of the lamp. In actual practice these lights would be used for instruction in the simultaneous impeded performances. However, reference could be made to them during the recorded performances whenever the experimenter noted a tendency toward a method change. A larger target, consisting of a circle of two and one half inches in diameter, surrounded each target button. These circles were painted flat-black and stood out in contrast against the light green of the test-board base. The target buttons were polished aluminum and contrasted with the flat-black. The pegs which were carried in the hands of the subjects during the testing were made of aluminum. They were one half an inch in diameter and one and five-eighths inches long.

The remaining piece of equipment constructed for the test-board was called the "shelf". This shelf, located directly above the targets,was to serve as an obstacle, and an impedance, to the hand(s) entering the peg(s) in the target area. The shelf consisted of a movable plywood partition the width of the test-board and was mounted in a vertical plane in a track three inches forward of the line of centers of the target buttons. The shelf was designed so that it could be placed in position and moved rapidly. The design was similar to a window sash, the adjustable sash representing the shelf. Its use can best be explained by using an analogy: if a window sash were closed to the point where an object to be passed through the window would just clear the sash, the person passing the object through the window would be forced to use care. The shelf in the experimental test-board was designed to act in a similar manner. When not in use it could be pushed up out of the way. The height at which it would stop when pushed into place was fitted to each subject by means of adjustable stops. Thus, the relative restriction to each subjects' hands remained the same. Small handles fastened to the rear of the shelf allowed the experimenter when standing behind the test-board to place the shelf in position and remove it with ease. This was accomplished by sliding the shelf downward or upward in its track. The shelf would remain where it was placed. It was painted flat-black to contrast with the light green of the test-board.

Timing Device.--The timing-device utilized was developed by Doctor W. Dale Jones in the Rich Laboratories of Industrial Engineering at Georgia Institute of Technology. Photographs of this device may be seen in the Appendix, Figures 2 and 3. This machine records time intervals on a paper tape. The paper tape is attached to a cylinder driven by a synchronous motor at ten revolutions per minute. A relay with a pen mounted on its movable leaf serves as a posting device. When the relay is energized an impression is made on the paper tape. This posting device was wired in such a manner that energizing of the relay produced only one mark on the tape no matter how long the posting circuit remained alive. Since the tape was driven continuously at ten revolutions per minute, and the circumference of the cylinder was twelve and one half inches, the distance between postings could be converted directly into time. Each one-eighth of an inch represented 0.001 minutes. It was, therefore, possible to obtain estimated movement time values to the nearest interpolated 0.0001 minutes. Indexing the posting device horizontally allowed the timing of up to eighteen separate performances on a single piece of tape. In this experiment each of the performances consisted of four postings: the beginning of the first basic movement; the end of the first basic movement which also represented the beginning of the impeded movement; the end of the impeded movement which also represented the beginning of the last basic movement; and the end of the last basic movement.

Experimental Subjects.--The experimental subjects were selected from a group of male college students. All were right-handed and possessed no eye trouble or obvious physical defects. "A consideration of the physical make-up of these students leads to the conclusion that there is no significant difference between them and employees encountered as applicants for industrial work of this sort (32)." So said Ralph M. Barnes in one of his experiments. This statement appears equally applicable in the experiments to be described, because of their very limited skill requirements. Five subjects were selected from a group of twenty on the basis of time consistency in performing the experimental task. Just as industry should not hire operators who do not possess the ability to do their jobs with mental and physical ease, the experimenter should not utilize subjects who could not complete the experimental tasks in a like manner. Since the correlation between any psychological test and performance on the task was unknown, the only recourse for selection of experimental subjects was to use what is referred to as a pre-test.

A pre-test consists of testing the subjects with the task that they are to perform. The criterion used for the selection of the subjects was their performance time consistency, as demonstrated in the pre-test. When collecting data a basic movement, then an impeded movement, and then another basic movement would be accomplished in one rhythmic performance. The subjects were to endeavor to expend the same effort throughout the performance. It was realized that equal effort on the impeded movement would produce a slow-down because of the impedance. However, the subjects who could complete the basic movements within each performance with more nearly equal time values would be more likely to have completed the impeded movement between these basic movements at the same pace. For successful conduct of the present experiment, it was necessary that individual subjects perform all movements within one performance at approximately the same pace.

In order to select qualified experimental subjects, twenty students were pre-tested. The procedure followed during the pre-test is described on page 32. The pre-test consisted of timing each of three single-impeded performances three times. Each of these performances consisted of a time value for a basic movement, a time value for an impeded movement, and a time value for another basic movement. The performances were completed as one rhythmic movement as described above. The exact criterion used for the selection of acceptable experimental subjects was that they complete seven of the nine performances with the two basic time values demonstrated within the performances differing less than six per cent. For example, if the basic times for a specific performance were 0.0145 minutes and 0.0155 minutes, they would not be within six per cent of each other: six per cent of the lesser value, 0.0145 minutes, would be 0.0009 minutes, therefore, the largest value the other basic time could be in order to qualify the performance would be 0.0154 minutes. Since it was observed that the subjects experienced considerable difficulty in performing seven of the basic time values within a closer time tolerance, six per cent was chosen. Five per cent had previously been chosen arbitrarily as the criterion. However, none of the subjects attained this goal. This was probably due to natural variation in the subjects' performance.

Seven of the twenty subjects qualified for the experiments by fulfilling the selection criterion. Although one of the subjects who qualified performed the basic movements within the six per cent limit, he also completed the impeded movement with almost the same time value. This subject could not be utilized because of his apparent speed-up on the impeded portions of the performance. Another of the students who qualified stated that although he considered himself right-handed he wrote and performed other tasks with his left-hand. It was felt that this subject might not possess the necessary dexterity to properly perform this experiment which was designed for right-handed subjects. Because of this fact this subject was disqualified as an experimental subject. Five experimental subjects were utilized. However, it was felt that these five carefully selected subjects would be adequate.

Work-Place.--The work-place consisted of the experimental test-board placed on a workbench. An adjustable chair was provided so that the forearms of each subject could be parallel to the test-board during the start of the transport movement. This was not accomplished during the pre-test because of time limitation; an average chair height was selected. The test-board was also adjusted closer to or further from each subject as necessitated by his arm length.

The timing device was positioned across the bench and to the left of the subject. The experimenter stood next to the timing device in a position permitting him to index the posting mechanism and operate the movement of the test-board shelf when necessary. The small neon lamps operated by the target buttons were placed in the rear of the test-board so that they could be observed by the experimenter. These lamps could not be seen by the subjects. The ventilation, lighting, and other time-determined conditions were kept, as nearly as possible, constant.

Relationship of Experimental Design to Statistical Analysis.--Ten sample recordings were collected from each experimental subject for each impeded movement. Details of this procedure may be found on page 38. These samples were compared by utilizing their mean (arithmetic average) values. For the purpose of statistical interpretation, the problem was re-stated in terms of a "null hypothesis". This was the hypothesis of no difference; mathematically it stated that the mean of the synthetic slow-down times was equal to the mean of the experimental or actual slow-down times. In terms of the present problem it stated that the sum of the individual impedance slow-downs was not significantly different from the slow-downs caused by these same impedances occurring together in the same movement. Stating the problem as a null hypothesis assumed that both means had come from a random sampling of normally distributed populations having a common mean value.

The method used to test the above hypothesis was the analysis of variance. The analysis of variance, according to R. A. Fisher its developer, "is not a mathematical theorem, but rather a convenient method of arranging the arithmetic (33)." It summarizes a mass of statistical data and reduces to a common form all the tests of significance which an experimenter may want to apply. The procedure followed when making up an analysis of variance table is too involved to summarize in this thesis, however, the step by step procedure used is given in Industrial Experimentation by K. A. Brownlee (34). The present experiment dealt with three factors; the experimental subjects, the compound impedances, and the method (experimental or synthetic). Therefore, a three factor analysis of variance was utilized. The results of this analysis are presented in Table 2. In the present experiment the test of significance is applied to the column of "mean squares". More specifically, it is applied between the "residual" mean square and the mean square for the source of variance between the two methods, symbolized by an "X" in the table. The statistic utilized to test the null hypothesis was the "F" distribution. This test compares the ratio of the magnitude of the two mean squares. By referring to a table of the variance ratio ("F" table), the probability that the means in question represent random samples from a common population may be determined.

A probability of five per cent, or five chances out of one-hundred, was chosen as a level of significance, since this is the level selected by most experimenters (35). Therefore, if there were five chances out of one-hundred or less that a ratio this large could have resulted from two means having come from a common population, the hypothesis would be rejected. A probability of one per cent or smaller was regarded as very significant. This meant that the hypothesis could be rejected with greater confidence. There would be one chance out of one-hundred that the two means could have come from the same population. Several other conclusions can be drawn from an analysis of variance table. These conclusions are presented in the Discussion of Results. It should be remembered that failure to reject a hypothesis does not establish its truth, but only indicates that the data offers no evidence against the hypothesis in terms of the standard agreed upon.

In conclusion, one author has said this about an experimenter who was testing the null hypothesis.

> If this hypothesis is rejected and he infers that some difference does exist between the means of his two groups that cannot be accounted for by random, uncontrolled variation, he may reason further that the difference observed is the result of his different experimental conditions. This reasoning, of course, is not part of the test of significance, but depends upon the structure of the experiment and the controls exercised by the experimenter. The test of significance is a test of statistical hypothesis (36).

It was necessary that the test of significance be indicative of the different experimental conditions. Therefore, extreme exactness and precaution were utilized throughout the instrumentation and experimental procedures.

CHAPTER IV

PROCEDURE

Impedances.--The transport of a peg from the posting button to the large target area and back was chosen as the basic movement. The time for this transport was considered the unimpeded movement time. The first of the impeded movements selected, which was a transport involving more precision, was a movement to a smaller target. This was accomplished by having the subject place the bottom of the peg against the target button. The second impedance was another form of restricted movement. The experimental subject was forced to exert care in order to avoid hitting an obstruction, the shelf, when moving to the target area. This shelf was placed above the targets and three inches in front of them so that in order to place the pegs in the target area the subject had to steer under the shelf. The last impedance, a two-handed movement of the pegs, was not an impedance, as such, but definitely produced an impeded movement as compared with a one-hand transport in the same direction. These three separate impedances made possible four compound impedances; the impedance due to the smaller target and the shelf, the impedance due to the smaller target and the two-handed movement, the impedance due to the two-handed movement and the shelf, and the impedance due to the smaller target and the shelf and the two-handed movement.

Pre-testing.--The pre-test was introduced to twenty students in a group orientation session, in which the students were instructed in the nature and conduct of the experiment. This background information was considered essential to obtaining the proper assistance from each. At this time the group was divided into three smaller groups to facilitate instruction and testing. The individual groups were instructed in the pre-test procedure in turn by the experimenter. The following paragraphs explain the orientation of one of these groups. It applies equally to all three.

The students were assembled at the workbench on which the test-board and timing device were placed. The basic movement was demonstrated and explained. Since the basic movement consisted of transporting a peg with the right-hand the distance of fifteen inches and back, the first step in the instruction of the prospective experimental subjects was to teach the proper method of holding the peg. The peg was to be grasped approximately one-quarter of an inch from its lower end with the first and second fingers. The third finger steadied the peg. This grasp was similar to holding a pen, however, the peg was to be held in a vertical plane rather than at an angle.

The basic movement consisted of moving the peg from the posting button to the large target area, the two and one-half inch black circle, and returning to the posting button. It was not necessary to touch the target with the peg, but just move it into the area directly above the target. When moving the peg into this area its base would not be over one inch above the test-board. The peg was to be held in a vertical plane during the entire performance. The posting button was to be brushed against with the second joints of the folded-under fingers during the movements. This basic movement was demonstrated to the students by the experimenter. Figure 2 in the Appendix shows the basic movement being performed by an experimental subject.

The first impeded movement consisted of moving the peg from the posting button to the small target button and back. During this movement the bottom of the peg was to be placed against the target button, thus lighting the neon glow-lamps. After this movement was demonstrated separately, the performance which was to be timed was demonstrated. This performance consisted of a basic movement, an impeded movement (the basic movement plus an impedance), and another basic movement all performed without pausing in one rhythmic movement. The students were cautioned to endeavor to expend equal effort in the whole performance and to work at a brisk or incentive pace, the maximum pace which can be maintained day after day without injury to health or mind. Working at a brisk pace is desired because there is "less variation in time (inconsistency) in performing a motion at a very fast speed than at a slower speed (37)." Also, the brisk pace is realistic, being indicative of the average performance of workers motivated by wage incentives.

As was stated previously, equal effort on an impeded movement and a basic movement would not produce the same time values. The impeded movement would be slower because of the impedance. Since the impeded movement is, in effect, a basic movement to which has been added an impedance, the slow-down caused by the impedance could be calculated by subtracting the average basic time for a performance from the impeded time within that performance. In order for this subtraction to be valid, it was essential that the entire performance be performed at the same pace (with the same effort). If the basic times were within six per cent of one another then the impeded time was assumed to have been performed at the average pace at which the two accompanying basic movements were performed. The above statements concerning consistency of effort, although brought out when explaining the first pre-test performance, apply equally to the rest of the pre-test and to the selected experimental subjects' final seven sets of recorded performances. The students were admonished of this fact.

In order for the experimental subjects to produce consistent effort, rhythm had to be established. Starting from a dead stop at the recording button would not be satisfactory since the first element accomplished was being timed and it would lack the necessary rhythm. Rhythm was established by adding a short unrecorded movement before the first recorded movement. The experimental subjects were instructed to start the performance with the right-hand at a point five to ten inches forward and a few inches to the right of the posting button. The selection of the exact location of this point was left to the convenience of the experimental subject. Starting from a point to the right of the posting button the experimental subject moved his right-hand to the posting button, brushing against it; moved to the large target area; moved back to the posting button, brushing against it; moved to the small target, touched it with the peg; moved back to the posting button again brushing against it. The addition of the unrecorded movement, the five to ten inch transport to the posting button, afforded the subjects the opportunity to establish a pace that would accustom them to the feeling of the movement prior to the recording of data. Therefore, the data would be less affected by this "warm-up" period than it would have been without the "starting" movement.

The next performance demonstrated to the subjects entailed an impedance, produced by the necessity of steering the hand to avoid touching the shelf. For the purpose of the pre-test, this shelf was not adjusted to each subject but was fixed at a height of four and one-eighth inches above the test-board. This was the average height used by subjects during a previous preliminary "test-run" of this movement. This was necessary to enable the twenty students to be pre-tested as rapidly as possible. Since, the pre-test was only concerned with the consistency of the basic movements within a performance, the amount of relative restriction caused by the shelf was unimportant.

In order that the subjects would not have the tendency to aim for the target button during this performance a black paper disk the same size as the large target area was taped over the large target, thus covering the button. The covering of the target was unimportant during the pre-test, since the time values of the basic movements were the only information utilized. It was desirable, however, to keep the pre-test as much like the recorded test as possible. This precluded the selected experimental subjects from learning any bad habits which might affect the actual experimental results. During the recording of this performance it was necessary for the experimenter to stand behind the test-board and raise or lower the shelf. After the subject had completed his first basic movement and his hand was returning to the posting button, the shelf was slid into place. Thus, the subject's hand was impeded by the shelf as it returned to the target area. As soon as the experimental subject's hand entered the target area the shelf was raised out of his way so that an unimpeded return movement could be made. This could be best accomplished if the experimenter focused his eyes on the target area. When the subject's hand left the target area during the first basic movement the shelf was lowered. When it entered the target area during the impeded movement the impeded movement the shelf was raised. The shelf was in place before the subject returned his hand to the posting button during the first basic movement. This allowed the experimental subject ample time to focus his eyes on the shelf and properly steer under it when performing the impeded movement. During this movement the experimental subject was instructed to continue to hold the peg in a vertical plane. Most experimental subjects, when first encountering the shelf, attempted to tilt the peg forward when approaching the shelf thus defeating its purpose. Therefore, a constant check had to be made to insure that this would not happen. The experimenter, standing behind the shelf, was in an excellent position to do this. Since the experimenter could not operate the shelf and demonstrate the performance to the students, this performance was demonstrated by utilizing one of the students as an experimental subject while the experimenter operated the shelf.

The last performance recorded during the pre-test had as an impedance the travel of the left-hand simultaneously and identically with the right-hand, i.e., a two-handed movement. This consisted of moving both hands simultaneously into the large target areas. A separate target, previously described, was provided for each hand. Each target was fitted with a black paper disk to cover the target button. During this movement the left-hand was to remain at the dummy button while the first and last basic movements were being performed. The left-hand would rest against the dummy button in the same manner that the posting button was brushed against by the right-hand. A peg was held in both hands in a like manner. After the first basic movement was completed the right and left-hands moved to their target areas simultaneously and then returned to the posting and dummy buttons respectively. It was stressed that this movement was to be a true simultaneous movement; the right-hand was not to lead or lag. Starting from a point to the right of the posting button the subject moved his right-hand to the posting button, brushed against it; moved to the large target area and back to the posting button; completing the first basic movement. Without pausing, the right and left-hands moved to the large target areas and back to the posting and dummy buttons, completing the impeded movement. The right-hand then moved to the large target area and back to the posting button for the final basic movement. This performance was demonstrated to the students.

Following this group instruction each student in the group was tested separately. The experimenter again demonstrated and discussed the type of performance in question before it was attempted by the student. During the student's practice session, extra instruction was given when needed. After five correct performances were accomplished consecutively the timing device was turned on and the recordings taken. Three recordings were made of each type of performance. Since there were three types of performances, a total of nine performances were accomplished by each student. These nine performances were timed on a single paper tape. The three groups of students were tested in this manner.

<u>Recorded Experimentation</u>.--The selected experimental subjects reported to the work-place one at a time and their data was taken in turn by the experimenter. Since they had already completed the performance involving the three single-impeded movements and were familiar with the testing procedure, very little preliminary instruction was necessary. However,

the experimental subjects were again reminded to complete the recorded performance as one smooth movement with the same effort applied to both the basic and impeded portions. They were also reminded to hold the peg in a vertical plane during the entire performance. The work-place was adjusted to each experimental subject as described on page 28. In addition the shelf stops were adjusted so that when the shelf was utilized the same relative restriction would be imposed on each experimental subject. In order to accomplish this, the subjects were asked to rest the base of the peg against the test-board while holding it in a normal grasp just below the shelf. The stops were then adjusted so that the shelf could not be lowered any further than one half of an inch above the highest knuckle on the hand holding the peg.

The performance involving the single-impeded and compound-impeded movements were each recorded twelve times. As was the practice in the pre-test, five correct performances of the type in question were consecutively accomplished before the recorded data was taken. When these five performances were completed the subject was considered "warmed up" and the recorded performances could then be started. During the recording any mechanical trouble, method change, failure to actuate the posting device, or etc. was noted. Performance times for these occurances, the values of which were not detectable during the experiments, were not used. When it was found necessary to discard a performance another performance was recorded in its place, since a total of twelve performances was desired for each of the seven impeded movements. This is explained further in the Discussion of Results, Analysis of Raw Data.

After the completion of the twelve recorded performances the experimental subject was permitted to rest for two minutes before undertaking the next type of performance. During this time the experimenter removed the used paper tape from the recording device and replaced it with a new one. The experimental subject's name and the number of the performance type to be recorded was written on the tape for identification. In order for the performance types to be readily identified they were titled according to the impeded movement occurring in each and were numbered one through seven, as listed below.

Single-Impeded Performances	1. The impedance due to the small target. 2. The impedance due to the shelf. 3. The impedance due to the left-hand.
Compound-Impeded Performances	4. The impedance due to the small target and the shelf. 5. The impedance due to the small target and the left-hand. 6. The impedance due to the shelf and the left-hand. 7. The impedance due to the small target and the shelf and the left-hand.

The recording of the three single-impeded performances will not be discussed again, since these types of performances were described fully when the pre-test was discussed. The compound-impeded performances were completed in the same manner as the single-impeded performances; the impeded movement was performed between two basic movements. The first compound-impeded performance has as an impedance a movement to the small target with the shelf in place above the target. Starting from a point to the right of the posting button the subject moved his right-hand to the posting button, brushed against it; moved to the large target area; moved to the posting button and brushed against it; thus completing the first basic movement. Without pausing and in the same rhythmic movement the subject moved his hand back toward the small target, steered under the shelf, and placed the base of the peg against the target button. He then returned his hand unimpeded to the posting button and brushed against it, thus completing the portion of the performance which included the impedance. To complete the recorded performance another basic movement was accomplished in the same manner as the first basic movement. The subject was reminded to move only to the large target area during the basic movement. This was necessary due to the fact that the small target remained uncovered during the entire performance but was utilized only on the impeded portion. The other characteristics of the single-impeded performances remained in effect during the compound-impeded performances. These characteristics are listed in detail at the end of the chapter.

The second compound-impeded performance had as the impeded portion the simultaneous movement to the small targets. During this movement the bases of both of the pegs were placed against the target buttons. When practicing this performance the glow-lamps were placed on the test-board so that the experimental subject could see them. The subject was asked to perform the movement in a true simultaneous manner thus lighting both lamps at the same time. After a brief practice session was completed the lamps were placed behind the test-board. Five correct performances were completed consecutively and then the recorded data was taken. This recorded performance was similar to the single-impeded performance which had as the impeded portion of the performance the two-handed movement. However, during this two-handed movement the pegs were moved to the small targets rather than to the large target area.

The third compound-impeded performance had as the impeded portion the two-handed movement to the large target with the shelf in place. This movement was similar to the two-handed movement also, with the exception that it was necessary to steer under the shelf in order to reach the target area. The experimental subjects were reminded to hold the pegs in a vertical plane throughout the performance. Since the small target was not utilized, the black paper disks were affixed to the large target area, thus covering the target buttons.

The last compound-impeded performance had as an impeded portion the result of all three impedances. During the impeded movement the experimental subject steered under the shelf with both hands and placed the bases of both pegs on the target buttons. As in the simultaneous move to the small targets, the subjects were to light both lamps together. The practice performances were completed with the lamps in sight of the subjects. This enabled them to see if they were performing the movement simultaneously. If not, they could correct their movement before the data were taken. Again, after correctly completing five practice performances in a row the twelve recorded performances were accomplished.

All of the experimental subjects' seven types of performances were completed at one sitting, with a rest of two minutes between each type of performance. In review, the following characteristics applied to all of the recorded performances: they consisted of a basic movement, an impeded movement, and another basic movement; equal effort was expended in a rhythmic movement pattern; the peg or pegs were held in a vertical plane throughout the performance; and the basic movement always consisted of moving the peg with the right-hand from the posting button to the large target area and back.

CHAPTER IV

DISCUSSION OF RESULTS

Analysis of Raw Data.--The markings on the paper tapes removed from the timing device were converted into estimated movement time values by the use of dividers and a scale. Each performance consisted of four impressions on the tape. Since the direction of travel of the tape was marked, the first posting could be easily found. The distance between this first posting and the second posting was the time needed to complete the first basic movement. The distance between the second posting and the third posting represented the time for the impeded movement. The distance between the third posting and the last posting was the time for the last basic movement. In order to facilitate interpretation, lines were drawn between the first and second, and the third and fourth impressions. Thus, the two basic movements were as clearly defined as was the impeded movement, being a blank space between two lined portions of the tape. The performances to be discarded because of mechanical trouble and noted deviations from specified performance method were lined through completely. These performances had been noted during the recording of the data.

After the twelve recorded performance times were measured for a particular tape, a comparison was made between the two basic movements in each performance. The performances with basic times differing greater than six per cent were marked. If more than two such performances occurred on a single tape, this "run" of performances was considered too inconsistent to have had the basic and impeded movements performed at the same pace. As a result, the entire "run" of twelve performances was retaken. A "run" with only two performances greater than six per cent was satisfactory and the remaining ten performances which had basic times within the six per cent limit were utilized. In the event that more than ten of the performances were within these limits, the ten with the most consistent basic times were utilized, i.e., the two performances with basic times differing the greatest would be discarded. In the event of a tie between two performances as to the one to be discounted, the performance chosen was selected at random. This occurred only twice. Recording twelve performances and utilizing only ten of them was also advantageous due to the fact that mechanical trouble or a missed posting was not always detected during the collection of the data. In this event, the set of data in question would not have to be retaken if ten acceptable performances, as specified by the experiment criterion remained.

Six of the experiments were repeated because they failed to meet the experiment criterion. The recorded set of performances from experimental subject C for impedance number two had to be taken three times because three or more performances in the first two sets of data had basic times differing greater than six per cent. Subject E, although asked to work at a brisk or incentive pace, completed his first set of performances at an almost normal pace. Because of this fact, this subject's performances were retaken at the proper pace. Three of the resulting seven sets of performances had three or more performances beyond the aforementioned six per cent limit. The performances for impedances one, three and six were retaken. The other subjects completed their part of the experiment with one set of performances for each impeded movement.

A normal time for the basic movement was arrived at by having a subject, other than the five used for the experiment, perform the basic movement ten times at a pace which he regarded as normal. The average of these ten performances was utilized as the normal basic time. The subject who accomplished the basic movement had had considerable industrial time study experience and was, therefore, cognizant of approximately what would be a normal pace. Regardless of this fact the validity of the normal time was immaterial since a comparison of the percentage increase in normal time due to the effect of the various impedances was desired. This can best be illustrated by using the following example.

(1) The average basic time produced by subject A when recording the performance of the set of performances involving impedance number one was 0.0151 minutes.

(2) Dividing this time into the assumed time for this movement of 0.0180 minutes resulted in a factorial speed-rating of 1.192. The factorial speed-rating represented the pace at which the experimental basic movement was performed as compared to the assumed normal time, in this case 119.2 per cent. Since the impeded movement was assumed to have been performed at the same pace, the normalized time would be the product of the factorial speed-rating and the impeded movement time. However, for the purpose of this experiment the increase in the time due to the impedance was normalized separately as described below.

(3) The average basic time of 0.0151 minutes was subtracted from the impeded time of 0.0159 minutes. This resulted in a time increase of 0.0008 minutes which when multiplied by the factorial speed-rating determined in step (2) yielded a normal time increase of 0.00095 minutes.

(4) The normal impeded time would be the sum of the normal time increase of 0.00095 minutes and the assumed normal time of 0.0180 minutes or 0.01895 minutes.

(5) This time represented an increase of 5.3 per cent over the normal basic time.

(6) If the normal basic time was actually 0.0170 minutes rather than 0.0180 minutes, the factorial speed-rating found in step (2) would have been 1.126.

(7) Multiplying the time increase of 0.0008 minutes by this new factorial speed-rating resulted in a normalized time due to the impedance of 0.00090 minutes.

(8) The normalized impeded time would, therefore, have been 0.01790 minutes, which again would be a 5.3 per cent increase over the normal basic time. Therefore, the percentage increase in the normal basic time as compared to the normal impeded time based on an erroneous basic time was valid.

Slow-down Comparisons.—The raw data for each type of performance for each subject was converted to normalized slow-down times in the manner discussed in steps (1) through (3) above. The means of the normalized slow-down times and the variance of the means were calculated for each impedance for each subject. A sample conversion of the raw data may be found in Table 1. A summary of the performances of the subjects is contained in Table 2. The performances in this table are numbered as before: numbers one through three represent the single-impeded movements, and numbers four through seven represent compound-impeded movements. By adding the single-impeded mean normalized slow-down times warranted for each compound-impeded movement a synthetic mean normalized slow-down time was arrived at for each compound-impeded movement. The mean normalized slow-down time for each compound-impeded movement was compared with these synthetic times. For example, the mean normalized slow-down time for the movement impedance due to the small target, performance number one, for subject A was 0.000977 minutes. The mean for the movement impedance due to care in moving under the shelf, performance number two, was 0.000653 minutes. Adding these two figures produced a synthetic normal impedance time for completing both impedances in the same movement, which is 0.001630 minutes. The mean for the normalized movement impedance to the small target with the shelf in place, performance number four, was 0.001540 minutes. This was 0.00090 minutes less than the synthesized, normalized impedance time found by adding the normalized times for the two single impedances. The significance of the difference between the experimental values and the respective synthetic values was determined by utilizing the analysis of variance.

In order to utilize the analysis of variance properly, it is necessary that all of the experimental data have a common error variance, or at least approximately so. The individual variance values for the experimental mean slow-down times were, therefore, tested in order to determine

Table 1. A Sample Conversion of the Raw Data, Subject A, Performance Type 1

Individual Performance Number	Basic Time	Basic + Target Time	Basic Time	Average Basic Time	Factorial Speed Rating	Slow-down due to Target	Normalized Slow-down due to Target
1.	.0151	.0159	.0151	.01510	1.192	.00080	.00095
2.	.0145	.0159	.0150	.01475	1.220	.00115	.00140
3.	.0145	.0160	.0153	.01490	1.208	.00110	.00131
4.	.0144	.0159	.0154	beyond six per cent basic-differential limit			
5.	.0144	.0150	.0145	.01445	1.246	.00055	.00069
6.	.0143	.0153	.0149	.01460	1.233	.00070	.00086
7.	.0147	.0157	.0149	.01480	1.216	.00090	.00109
8.	.0145	.0155	.0148	.01465	1.229	.00085	.00104
9.	.0135	.0150	.0149	beyond six per cent basic-differential limit			
10.	.0148	.0155	.0150	.01490	1.208	.00060	.00072
11.	.0145	.0155	.0150	.01475	1.220	.00075	.00092
12.	.0148	.0155	.0149	.01485	1.212	.00065	.00079

$\Sigma x = .00977$

$\Sigma x^2 = .0000100529$

Table 2. Single-Impeded, Compound-Impeded, and Synthesized Mean Normal Slow-down Time Values

Subject	Performance Type	Experimental Average Slow-down Time ($\bar{x}_E$)	Performance Types Comprising Synthetic Value	Synthetic Value ($\bar{x}_S$)	Experimental Variance ($\sigma_E^2 x10^{-11}$)	Synthetic Variance ($\sigma_S^2 x10^{-11}$)
A.	1.	.000977	-	-	5,076 *	-
	2.	.000653	-	-	5,744	-
	3.	.000698	-	-	4,746	-
	4.	.001540	1 + 2	.001630	7,046	10,820
	5.	.001518	1 + 3	.001675	13,756	9,822
	6.	.001120	2 + 3	.001351	7,748	10,490
	7.	.002131	1 + 2 + 3	.002328	18,497	15,566
B.	1.	.000910	-	-	5,000	-
	2.	.000683	-	-	2,706	-
	3.	.000912	-	-	11,756	-
	4.	.001171	1 + 2	.001593	3,247	7,706
	5.	.001623	1 + 3	.001822	22,696	16,756
	6.	.001325	2 + 3	.001595	5,646	14,462
	7.	.001881	1 + 2 + 3	.002505	27,591	19,462
C.	1.	.000982	-	-	6,252	-
	2.	.000479	-	-	1,329	-
	3.	.001294	-	-	6,702	-
	4.	.001250	1 + 2	.001461	13,116	7,581
	5.	.002039	1 + 3	.002276	7,419	12,954
	6.	.001541	2 + 3	.001773	18,711	8,031
	7.	.002516	1 + 2 + 3	.002756	25,320	14,283

(continued)

Table 2. Single-Impeded, Compound-Impeded, and Synthesized Mean Normal Slow-down Time Values (continued)

Subject	Performance Type	Experimental Average Slow-down Time ($\bar{x}_E$)	Performance Types Comprising Synthetic Value	Synthetic Value ($\bar{x}_S$)	Experimental Variance ($\sigma_E^2 x10^{-11}$)	Synthetic Variance ($\sigma_S^2 x10^{-11}$)
D.	1.	.001007	-	-	2,252	-
	2.	.000641	-	-	2,233	-
	3.	.001148	-	-	8,534	-
	4.	.001420	1 + 2	.001648	16,944	4,485
	5.	.001543	1 + 3	.002155	16,178	10,786
	6.	.001483	2 + 3	.001789	19,784	10,767
	7.	.002424	1 + 2 + 3	.002796	10,088	13,019
E.	1.	.001485	-	-	23,838	-
	2.	.001401	-	-	5,059	-
	3.	.001533	-	-	11,442	-
	4.	.002519	1 + 2	.002886	59,065	28,897
	5.	.002962	1 + 3	.003018	28,690	35,280
	6.	.002539	2 + 3	.002934	25,789	16,501
	7.	.004475	1 + 2 + 3	.004419	39,782	40,339

*Example: 5,076 represents 0.00000005076 if this assumption was met. This was determined by testing for homogeneity of variance of the data with a standard deviation (the square root of the variance) control chart. This chart establishes limits within which all of the standard deviation values are homogeneous. Subject E had one standard deviation value outside of the upper control limit and, therefore, his data was not homogeneous with that of the other subjects. Recalculation of the control limits without the data attributed to subject E failed to show any other "out of control" standard deviation values. The individual variances for the compound-impeded performances for all of the subjects were, therefore, uniform enough to meet the above assumption with the exception of those variances attributed to subject E. Since his data was not homogeneous with that of the other subjects, subject E could not be used in the analysis.

The experimental and synthetic normalized slow-down times were coded by converting them to the nearest 0.00001 minutes and moving the decimal point to the right five places. The coded data is presented in Table 4. This coded data was then converted into the analysis of variance table, presented in Table 5. Statements concerning this conversion were made in Chapter III under the heading "Relationship of Experimental Design to Statistical Analysis." The comparison of the "residual" mean square value with the other mean square values revealed that there was a very significant difference (beyond the one per cent level): between the experimental method and synthetic method, between each compound impedance, and between each experimental subject. Since the significant difference between the experimental method and the synthetic method was beyond the

Table 3. Coded Data for Analysis of Variance

Experimental Subjects	Method	Compound Impedances			
		I_4	I_5	I_6	I_7
O_a	X_e	154*	152	112	213
	X_s	163	168	135	233
O_b	X_e	117	162	133	188
	X_s	159	182	160	251
O_c	X_e	125	204	154	252
	X_s	146	228	177	276
O_d	X_e	142	154	148	242
	X_s	165	216	179	280

Original Data = (Coded Data) x 10^{-5}

*Example: 154 = .00154

Where:

I = Compound Impedance
O = Experimental Subjects
X = Method
e = Experimental
s = Synthetic

Table 4. Analysis of Variance Table

Source of Variance	Degrees of Freedom	Sums of Squares	Mean Squares	F
Between O	(o-1) = 3	5,262.4	1,754.1	18.7*
Between X	(x-1) = 1	6,786.2	6,786.2	72.5*
Between I	(i-1) = 3	47,075.2	15,691.7	167.6*
O x X interaction	(o-1)(x-1) = 3	702.3	234.1	2.5
X x I interaction	(x-1)(i-1) = 3	182.5	60.8	1.5
I x O interaction	(x-1)(o-1) = 9	4,693.3	521.5	5.9*
Residual**	(o-1)(x-1)(i-1)=9	843.0	93.6	
Total	oxi-1 = 31	65,544.9		

*Significant at the 0.01 per cent level or better, unmarked values are not significant.

**The residual variance is a measure of the variance of the original data.

$$\sigma_{\bar{x}}^{2} = \frac{\sigma_x^2}{n}$$

$$\sigma_x^2 = n\sigma_{\bar{x}}^{2}$$

$$= 10 \times 93.6 \times 10^{-10}$$

$$= 9{,}360 \times 10^{-11} \approx \text{ original data variance}$$

The arithmetic average of the variances of the original data is 13, 148×10^{-11}. The residual variance and the average variance compare favorably and indicate that there is no inflation in the residual variance due to excessive interaction.

Table 5. Compound-Impeded Slow-down Percentage Comparisons

Impedances	Actual Percentage Increase Above Normal Basic Time	Synthetized Percentage Increase Above Normal Basic Time	Units of Per Cent Difference Between Synthetic and Actual	Percentage Error
I_4	7.47	8.80	1.33	+17.8
I_5	9.33	11.02	1.69	+18.1
I_6	7.60	9.04	1.44 (1.5)*	+18.9 (18.3)*
I_7	12.43	14.43	2.00	+16.1

*These figures represent the arithmetic average values for the compound-impeded movements involving two impedances (I_4, I_5, I_6). I_7 contains three impedances.

one per cent level, the null hypothesis could be rejected with a great deal of confidence. Therefore, the time effects of the single, motion impedances tested are not additive when they occur in a single movement. It would be expected that there would be a significant difference between the experimental subjects since people are generally considered to be different from one another and, therefore, will not produce exactly the same normal time value on any given task. The significant difference revealed between the compound impedances is, likewise, natural since the impedances selected were different from one another and produced different slow-down time values. A significant interaction was also revealed between the compound impedances and the subjects. This indicated that the mean time for the compound impedances varies from one subject to another. No significant interaction occurred between the method and the compound impedance, and the method and the subjects. Therefore, although the experimental subjects' slow-down times varied with the compound impedances the effect on the compound impedance slow-down times was the same.

The normalized slow-down time exhibited by the subjects were practically uniform, with the exception of subject E whose times were somewhat greater than those of the other subjects. As mentioned previously, this subject's data also contained the largest variance values. Since the subjects were not selected on the basis of skill, but on consistency of performance, it was likely that this subject was the least skilled. This subject also had the most difficulty in producing acceptable performances and it is, therefore, possible that he was working more deliberately. An investigation of the effects of skill on compound impedances might clarify this subject's performance.

The mean values of like impedances for each of the subjects, with the exception of subject E, were pooled and a grand mean was calculated for each impedance. Subject E was eliminated for the reasons previously stated. The grand mean values were utilized in order to derive a percentage slow-down for each single and compound-impeded movement. The results of these calculations are listed in Chapter VII and in Table 5. As a result of these calculations it was found that the average error between the synthesized slow-down time and the actual slow-down time was 18.3 per cent for the compound-impeded movement involving two impedances. The error for the compound-impeded movement involving three impedances was 16.1 per cent.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations to be discussed were based only on the experimental results, previously discussed in detail. They entail the following limitations:

1. A hand transport motion was tested. This motion was:

   a. Performed from a seated position;

   b. Performed in a horizontal plane;

   c. A reach motion involving reaching directly in front of the body a distance of fifteen inches perpendicular to the edge of the table at which the subject was seated;

   d. Unimpeded during the return performance;

   e. Required semi-skill on some portions;

   f. Performed at a brisk pace;

   g. Performed with a one-half inch diameter and one and five-eighths inches long peg in the right hand. When the left hand was used it also carried a like-dimensioned peg in a similar manner. The peg was:

      (1) Held with the first and second fingers and steadied with the third;

      (2) Held in a vertical plane.

2. The impeded movement was performed between two right hand basic movements in one rhythmic motion. These movements were assumed to have been performed at the same pace. This assumption was made for the following reasons:

   a. Rhythmic motion speed was possible throughout the performance.

b. Rhythm was established before the recording of the data.

c. The subjects were carefully instructed and repeatedly reminded to strive for consistent pace throughout the performance.

d. The subjects moved at a brisk rate of speed, minimizing the chances for difference of movement speed between portions of the movement.

e. Inconsistencies were determined by comparison of the basic times. Only consistent performances were utilized.

3. The impedances tested were:

a. A movement to a seven-eighths of an inch target;

b. A movement under an obstruction with a clearance of one-half an inch above the knuckles for each subject;

c. A simultaneous and identical movement of the left hand.

4. Only five subjects were tested. These five subjects were:

a. Selected on the basis of accurately measured consistency in performing a task at a uniform pace;

b. Untested or not selected on the basis of skill, although a small degree of skill was required to perform the impeded movements;

c. Selected from a group of twenty male college students;

d. Highly motivated because of the experimental nature of the work.

5. Only four of the five subjects tested were used in the statistical analysis of the data.

a. The fifth subject was eliminated because of excessive variance (failure to meet the assumption of homogeneity of variance).

b. The results cannot be over-generalized because of the small sample size.

<u>Conclusions</u>.--In view of the above limitations and the results of the research, the following conclusions may be made:

1. The evidence indicates that the time effects of single, motion impedances are not additive when two or three of them occur in a single movement.
2. When two impedances are involved in a compound-impeded movement, the synthetic time value which is calculated by the addition of the individual impedance slow-down times can be corrected by multiplying by a factor of 0.985.
3. When three impedances are involved in a compound-impeded movement, the synthetic time value which is calculated by the addition of the individual impedance slow-down times can be corrected by multiplying by a factor of 0.980.
4. The following percentage increases above the normal basic time apply to the impedances tested:
   a. A movement of a peg (one-half inch in diameter and one and five-eighths inches long) held upright in the right hand to a seven-eighths of an inch target, 5.39 per cent;
   b. A movement of a peg held in the right hand under an obstruction with a clearance of one half of an inch above the knuckles, 3.41 per cent;
   c. A simultaneous movement of a peg held in the left hand during an otherwise unimpeded fifteen inch forward movement of a peg held in the right hand, 5.63 per cent;
   d. A movement involving "a" and "b", 7.47 per cent;
   e. A movement involving "a" and "c", 9.33 per cent;
   f. A movement involving "b" and "c", 7.60 per cent;
   g. A movement involving "a", "b", and "c", 12.43 per cent.

General Recommendations.--The conclusions of this research are based on a fifteen inch movement involving three distinctly different impedances. It is recommended that other impedances be investigated in a similar manner in order to determine their compound time effects. Other research suggests that the time effects of certain other impedances are not additive when more than one is performed in a single movement (38). More information, attainable through research methods described herein, is needed concerning this problem in order that more general conclusions can be made concerning the time effect of compound impedances. Perhaps the times of certain types of impedances are additive while others are not. The compound effects may also be affected by the distance of the transport-movement. A short movement may product a more than additive effect, while an extremely long movement may produce a less than additive effect. The amount of skill possessed by an operator may also have some effect on the additive nature of the impedance times.

In order for the above percentage values to be more firmly established for these particular impedances or others, it is suggested that further experimentation be conducted with a larger number of experimental subjects. This experimentation can be accomplished by the means described in this thesis. The experimental subjects should consist of industrial workers who perform repetitive operations involving movements similar to those being tested. This will eliminate the necessity of testing the subjects on the basis of consistency since this test was designed to select experimental subjects that would be representative of industrial workers performing these operations. Therefore, the experimental subjects will consist of a random sample rather than a selected group. This will affect the analysis of the data in that the results will apply to the population (all of the industrial workers performing this type of operation) rather than to the particular group selected. This assumes that a random sample of the population has been selected. In terms of the analysis of variance, it will mean that a "Model 2" analysis can be utilized rather than a "Model 1" analysis. Statistically, the conclusions will then apply to the population and not to the selected group. The conclusions of the present experiment apply to industrial workers insofar as the selected subjects apply to industrial workers.

In conclusion, in the basis of the limited, yet carefully executed, research of this thesis, it appears that typical impedances occurring in combination are not additive, i.e., the total impedance time of two or more impedances occurring in combination is not equal to the sum of the respective time impedances when occurring separately.

APPENDIX

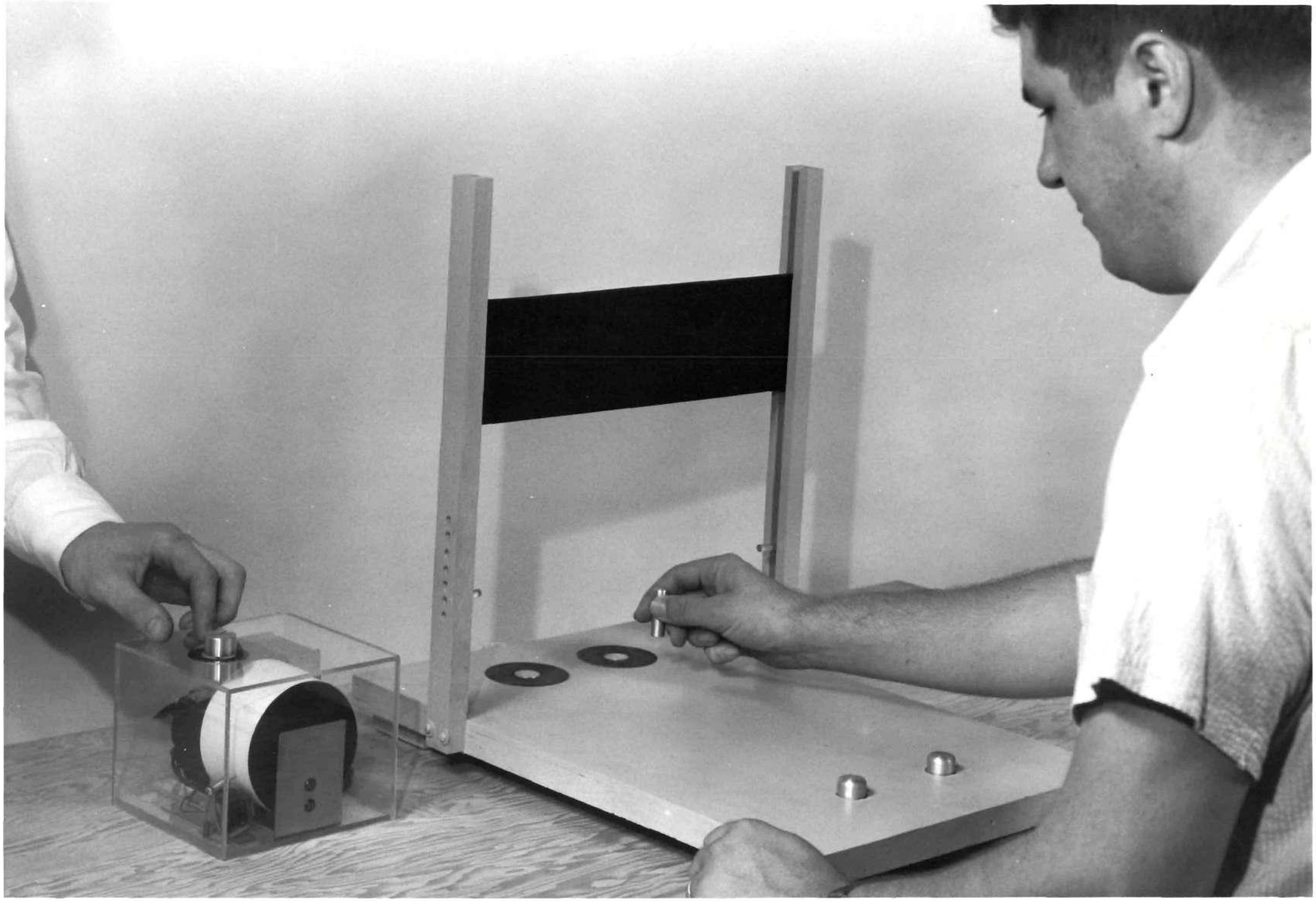

Figure 1. Experimental Test-board with Experimental Subject Performing the Basic Movement

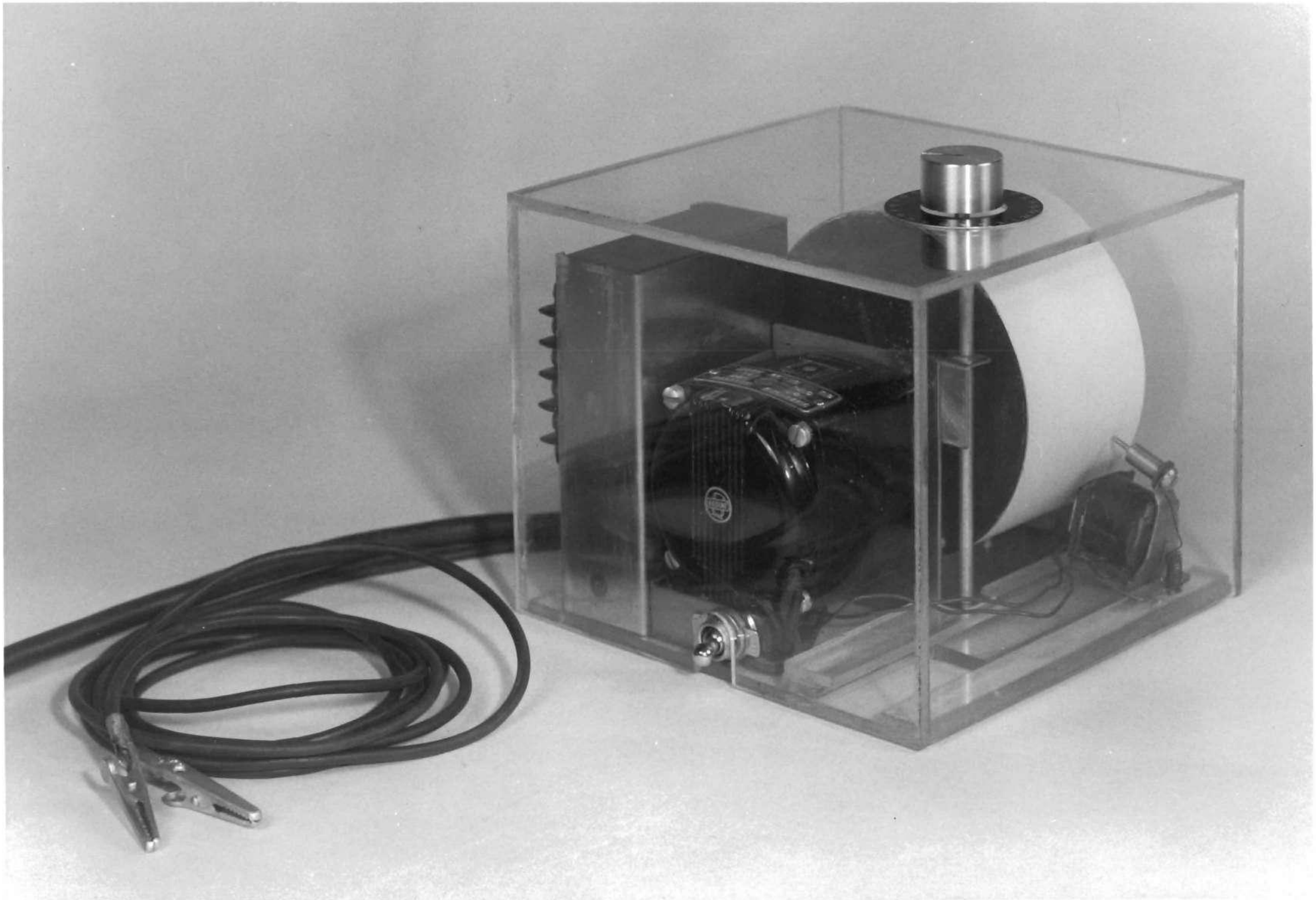

Figure 2. Timing Device Developed by Doctor W. Dale Jones

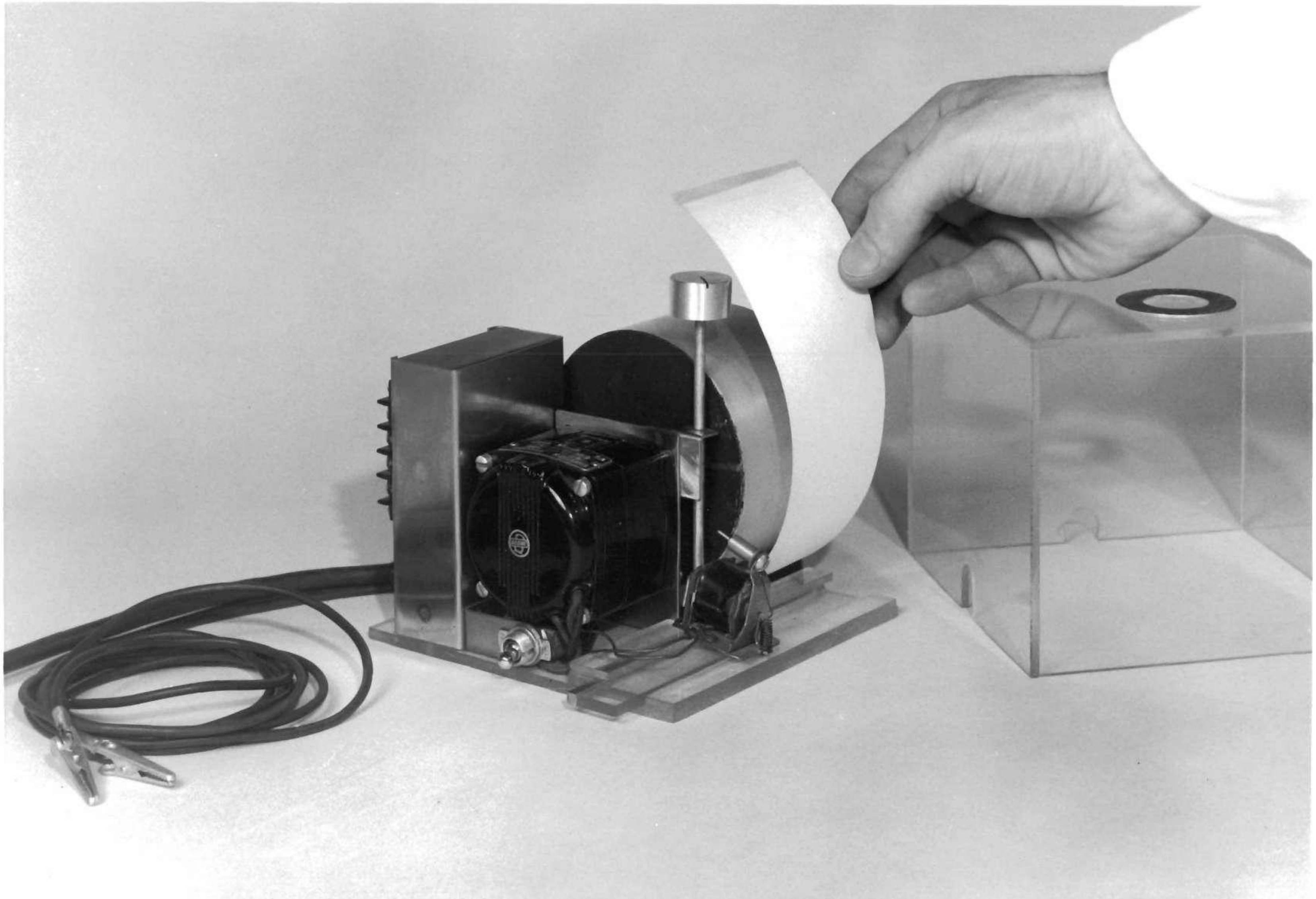

Figure 3. Removing the Tape from the Timing Device

BIBLIOGRAPHY

1. Taylor, F. W., Shop Management. New York: Harper and Brothers, 1911, p. 167.

2. Ibid., p. 177.

3. Yost, Edna, Frank and Lillian Gilbreth, Partners for Life. New Brunswick, New Jersey: Rutgers University Press, 1949.

4. Segur, A. B., The Story of Motion-Time-Analysis. Oak Park, Illinois: A. B. Segur and Company, p. 7.

5. Gomberg, William, A Trade Union Analysis of Time Study. Chicago: Science Research Associates, 1948, pp. 52, 160.

6. Barnes, R. M., Motion and Time Study. New York: John Wiley and Sons, Inc., 3rd ed. 1949, pp. 176-178.

7. Ibid., pp. 435-459.

8. Holmes, W. G., Applied Time and Motion Study. New York: The Ronald Press Company, 1938, p. 244.

9. Work-Factor Company, The, Abbreviated Work-Factor Time-Standards. New York: The Work-Factor Company, 1951, p. 1.

10. Ibid., pp. 1 - 6.

11. Maynard, H. B., Stegermerton, G. L., and Schwab, J. L., Methods-Time Measurement. New York: McGraw-Hill Book Company, 1948.

12. Ibid., p. 8.

13. Lynch, Herbert, "Basic Motion Timestudy," The Journal of Industrial Engineering, 4, August, 1953, pp. 4-6.

14. Jones, W. D., Synthetic Time Study. Unpublished short course text material, Georgia Institute of Technology, 1952.

15. Brady, P. J., "Work-Factor Analysis Saves Money, Time, Complaints," Factory Management and Maintenance, 109, June 1951, pp. 110-112.

16. MacLatchie, Robert, "Wage Incentives from Motion Time Standards," Proceedings of the Material Time and Motion Study Clinic. Chicago: The Industrial Management Society, 1946.

17. Gomberg, William, "The Relationship between the Unions and Engineers," Mechanical Engineering, 64, June, 1943, p. 428.

18. Davidson, H. O., "Functions and Bases of Time Standards," Research Committee on Synthetic Time Systems, Columbus, Ohio: American Institute of Industrial Engineers, 1952, p. 140.

19. Maynard, op. cit., p. 132.

20. Lynch, op. cit., p. 4.

21. Mundel, M. E., Motion and Time Study, Principles and Practice. New York: Prentice-Hall, Inc., 1950, p. 363.

22. Barnes, R. M., and Mundell, R. E., "Studies of Hand Motions and Rhythm Appearing in Factory Work," University of Iowa Studies in Engineering, Bulletin No. 12, Iowa City: University of Iowa, 1938.

23. Quick, J. W., Shea, W. J., and Koehler, R. E., "Motion-Time Standards," Factory Management and Maintenance, 103, May 1945, pp. 97-108.

24. Work-Factor Company, The, Work-Factor Data. Reprinted with the permission of The Work-Factor Company, Georgia Institute of Technology, 1952.

25. Maynard, H. B., Stagemerton, G. J., and Schwab, J. L., "Methods-Time-Measurement," Factory Management and Maintenance, 106, February 1948, pp. 97-104.

26. Davidson, op. cit., pp. 134-141.

27. Maynard, Methods-Time-Measurement, p. 121.

28. Woods, J. D., and Gordon, Ltd., Basic Motion Timestudy Manual. Toronto: J. D. Woods and Gordon, Ltd., 1951.

29. Mundel, op. cit., p. 331.

30. Mundel, op. cit., p. 333.

31. Barnes, R. M., and Mundel, M. E., "A Study of Simultaneous, Symmetrical Hand Motions," University of Iowa Studies in Engineering, 97, August 1939.

32. Barnes, R. M., and Perkins, J. S., "A Study of the Development of Skill During Performance of a Factory Operation," Transactions of the American Society of Mechanical Engineers, 63, May 1941.

33. Edwards, A. L., Experimental Design in Psychological Research. New York: Rinehart & Company, Inc., 1950, p. 175.

34. Brownlee, K. A., Industrial Experimentation, New York: Chemical Publishing Company, Inc., 1952, pp. 88-93.

35. Edwards, op. cit., p. 28.

36. Ibid., p. 28.

37. Wadsworth, H. M., Jr., A Study of the Time Effects of Distance, Direction, and Simultaneity on Manual Transport Motions. Unpublished M. S. Thesis, Georgia Institute of Technology, 1954, p. 21.

38. Ibid., p. 48.